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Municipal incinerated bottom ash use as a cement component in concrete

Ciarán J. Lynn
Doctoral Researcher, School of Civil Engineering, University of Birmingham, Edgbaston, Birmingham, UK

Ravindra K. Dhir
Professor, School of Civil Engineering, University of Birmingham, Edgbaston, Birmingham, UK (corresponding author: r.k.dhir@bham.ac.uk)

Gurmel S. Ghataora
Senior Lecturer, School of Civil Engineering, University of Birmingham, Edgbaston, Birmingham, UK

The characteristics of municipal incinerated bottom ash (MIBA) and its potential use as a cementitious component in concrete applications are examined through an analysis and evaluation of global experimental data. As raw feed in cement clinker production, MIBA can be incorporated at minor contents without compromising performance. To avoid damaging hydrogen gas expansive reactions arising due to the metallic aluminium in the ash, treatment of MIBA is required for use as cement components in cement, mortar and concrete. As such, thermal and chemical treatments, as well as tailored slow and wet grinding treatments, have been effective in improving performance. The hydrogen gas expansion associated with MIBA can beneficially contribute towards the lightweight properties required for aerated concrete, with the ash serving as an alternative to aerating agents and also contributing to strength development. Initial work on controlled low-strength materials has highlighted MIBA as a potential cement replacement material that can meet the low-strength requirements.

Introduction

Incineration of municipal solid waste (MSW) is being increasingly adopted as an alternative to landfilling, with rising incineration rates of 20%, 23% and 27% reported in the 28 European countries in 2006, 2010 and 2014, respectively (Eurostat, 2016). This waste management option results in large reductions in the quantity of waste to be managed, leaving behind residues approximately 30% by mass of the original waste, of which 80–90% is municipal incinerated bottom ash (MIBA). For every tonne of MSW incinerated, approximately 0·25 t of MIBA is generated.

With the 27% incineration rate and a total of 64 Mt of MSW incinerated in 2014 in the European Union (Eurostat, 2016), it is estimated that approximately 16 Mt of MIBA may be generated annually in these EU countries. On a global scale, based on data gathered for 97% of the world's population, including records from around 700 waste-to-energy treatment plants, the Waste Atlas Partnership calculated that 1·84 billion tonnes of MSW is produced worldwide per annum (WAP, 2013).

The quantity of MIBA produced presents a significant management challenge for governing bodies. Countries such as Belgium, Denmark, Germany and The Netherlands lead the way with extensive use of MIBA, primarily as fill and in road pavement materials (An *et al.*, 2014; ISWA, 2006; Qing and Yu, 2013). The practical use of MIBA in concrete-related applications is much less developed, particularly as a cementitious component in ground form, which is the focus of this paper. However, as the cement production process carries a high carbon dioxide footprint and with increasing importance placed on sustainability, there is significant incentive to develop this higher value use of MIBA. Indeed, a number of other additions, such as fly ash and ground granulated blast-furnace slag (GGBS), have been successfully established as concrete constituents.

The project

This paper presents a critical assessment of the characteristics of MIBA and its use as a cementitious component in concrete-related applications through an analysis and evaluation of globally published experimental results on this subject. With substantial work undertaken, the coherent and incisive dissemination of the combined resources aims to assist in progressing the sustainable use of MIBA, covering its use as raw feed in cement clinker production and cement components in pastes, mortar, concrete, controlled low-strength materials (CLSMs), self-compacting concrete and aerated concrete.

Significant work has been undertaken on the use of MIBA as a cement component in concrete applications and, although only starting quite recently in 1998, the interest has been trending upwards, with a particularly large number of publications produced over the last three years (2014–2016). Research in this area has been undertaken in 12 countries worldwide, with the largest share of the work coming from Europe (59%), followed by Asia (38%) and North America (3%). The largest individual contributions have come from Italy, China and Taiwan. An overwhelming quantity of data was obtained on the characteristics of MIBA. To retain clarity in this text, references containing solely numerical data on the material properties are listed in Appendices in the Supplementary Material.

Material characteristics

Oxide composition

The most abundant oxides found in MIBA are silicon dioxide (SiO_2), calcium oxide (CaO) and aluminium oxide (Al_2O_3), with iron oxide (Fe_2O_3), sodium oxide (Na_2O), sulfur trioxide (SO_3), phosphorus pentoxide (P_2O_5), magnesium oxide (MgO) and potassium oxide (K_2O) present in smaller quantities (references given in Appendix 1 of the Supplementary Material). These main oxides are similar to what is customarily found in common cementitious materials and, as such, a ternary plot of their contents in worldwide bottom ash samples is presented in Figure 1 (based on data from the references in Appendix 1).

It is evident that the bulk of the samples fall close to latent hydraulic and pozzolanic regions, with MIBA generally having a calcium oxide content above the pozzolanic fly ash, but below the latent hydraulic GGBS. Compared with fly ash in concrete, ASTM C618 (ASTM, 2015) specifies that the silicon dioxide + aluminium oxide + iron oxide content should be a minimum of 70% and 50% for class F and class C fly ash, and it was found that 16% and 66% of MIBA samples satisfied these respective limits.

The MIBA was found to have an average sulfur trioxide content of 2·4%, which satisfies the maximum 3% and 5% limits specified in EN 450 (EN, 2012) and ASTM C618 (ASTM, 2015) for fly ash in concrete. However, approximately one third of the MIBA samples exceeded the more stringent EN 450 (EN, 2012) limit and, as such, could require treatment if used in concrete. Phosphate and magnesium can affect the setting behaviour and soundness of cementitious products, though the contents present in MIBA (average contents of 2·4% phosphorus pentoxide and 1·9% magnesium oxide) are well below the 5% and 4% limits specified for fly ash in EN 450 (EN, 2012). Minor amounts of alkalis (sodium oxide) are also present in the ash, on average at contents of 2·9%. This is within the 5% limit outlined in EN 450 (EN, 2012) and, similarly to fly ash, MIBA may have a net positive effect on alkali–silica behaviour as a cement replacement, due to alkaline dilution.

Loss on ignition (LOI)

Values of LOI for the tested MIBA samples are presented in Figure 2 in ascending order (references in Appendix 2 of the Supplementary Material). The material was determined to have an average LOI of 5·8%, though this is slightly distorted by a number of very high values. LOI limits vary for additions, though compared with fly ash requirements, 61% and 67% of the MIBA samples satisfied the respective requirements of 6% in the American standard ASTM C618 (ASTM, 2015) and 7% in the UK National Annex to EN 197 (EN, 2011). As excessive organics can impair the strength and durability of concrete, this parameter is important to monitor after the incineration stage, in assessing the potential for use of MIBA as a cementitious component.

Mineralogy

Amorphous contents of 15–70% have been reported for quenched MIBA (Bayuseno and Schmahl, 2010; Dhir *et al.*, 2002; Inkaew *et al.*, 2016; Paine *et al.*, 2002; Rubner *et al.*, 2008; Wei *et al.*, 2011), suggesting that the material may have some degree of reactivity when ground to a cement fraction. Quartz was the most abundant mineral found in the ash,

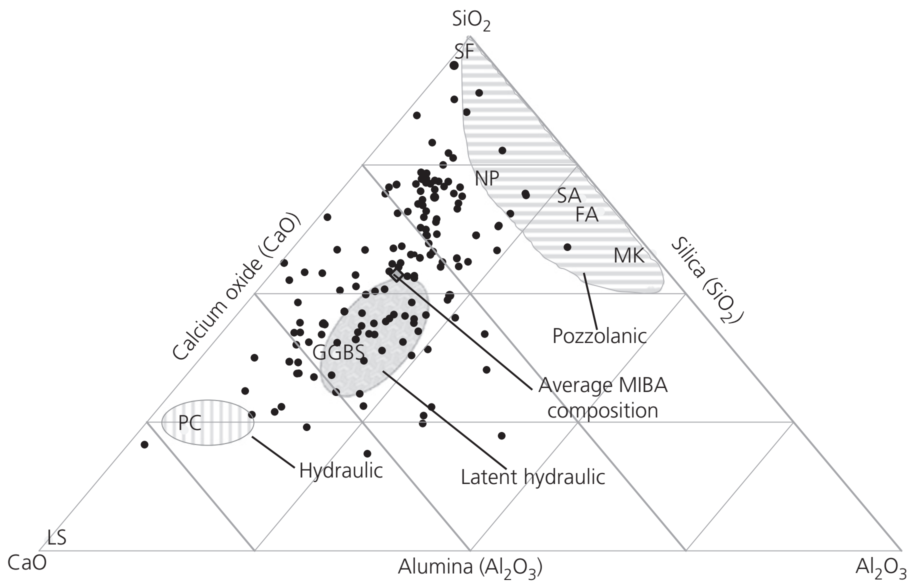

Figure 1. Ternary plot of the composition of the main oxides in MIBA: PC = Portland cement, GGBS = ground granulated blast-furnace slag, FA = fly ash, MK = metakaolin, SA = shale ash, NP = natural pozzolan, SF = silica fume and LS = limestone

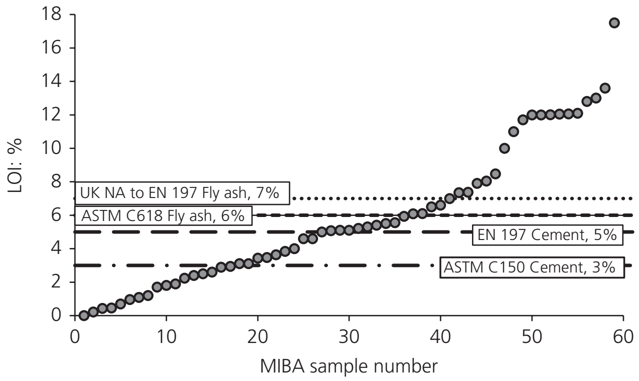

Figure 2. Loss on ignition values of MIBA samples in ascending order

followed by calcite, hematite, magnetite and gehlenite (frequently present) and then a wide range of other silicates, aluminates, aluminosilicates, sulfates, oxides and phosphates appearing infrequently (references in Appendix 3 of the Supplementary Material).

Element composition

Data on the element composition of the MIBA samples is presented in Table 1, sorted from highest to lowest average contents. For use as a cementitious component, the chloride and metallic aluminium contents are particularly important. Chloride limits of 0·1% are specified in EN 197 (EN, 2011) for common cements and EN 450 (EN, 2012) for fly ash in concrete and, as such, the average value of 0·9% in MIBA indicates that further treatment would be required to reduce this to the accepted level.

The issue of the metallic aluminium is a problem more specific to MIBA use in concrete and has been highlighted as a key concern by Tyrer (2013), Pecqueur *et al.* (2001), Müller and Rubner (2006) and Weng *et al.* (2015). Aluminium reacts in the alkaline environment in cement and is accompanied by the formation of hydrogen gas bubbles, leading to expansive behaviour and spalling damage that can greatly compromise the concrete performance. In aerated concrete, the expansive reaction is advantageous but, in other applications, treatment is suggested to either remove the metallic aluminium or dissipate the expansive reactions before its use in concrete.

The presence of soluble lead, zinc, phosphates and copper in MIBA may potentially affect the setting behaviour of concrete, as these constituents are sometimes used in admixtures as set retarders.

Density

Specific gravity results for MIBA are presented in Figure 3, with the samples divided into (*a*) unspecified or screened to remove oversized fraction or sieved as aggregate, (*b*) subjected to metal recovery treatment and (*c*) ground as cementitious

Table 1. Element composition of MIBA (references in Appendix 4 of the Supplementary Material)

	Number of samples	Average: mg/kg	Standard deviation: mg/kg	Coefficient of variation: %
Silicon	13	210 893	64 046	30
Calcium	31	117 750	59 238	50
Iron	36	53 455	36 393	68
Aluminium	35	44 047	15 634	35
Sodium	24	22 812	16 526	72
Magnesium	29	14 967	8664	58
Chlorine	37	8944	9443	106
Potassium	29	8256	4716	57
Titanium	12	6632	5553	84
Sulfur	27	5184	2208	43
Phosphorus	10	4866	3987	82
Zinc	78	4044	2974	74
Copper	76	3071	2796	91
Lead	73	1641	1205	73
Barium	31	1312	910	69
Manganese	41	921	599	65
Chromium	77	398	325	82
Strontium	17	379	179	47
Antimony	18	253	714	282
Nickel	58	182	132	73
Vanadium	22	167	286	172
Cobalt	24	50	104	207
Arsenic	46	50	61	123
Molybdenum	19	28	27	99
Cadmium	50	14	23	159
Mercury	17	1·4	4·0	290

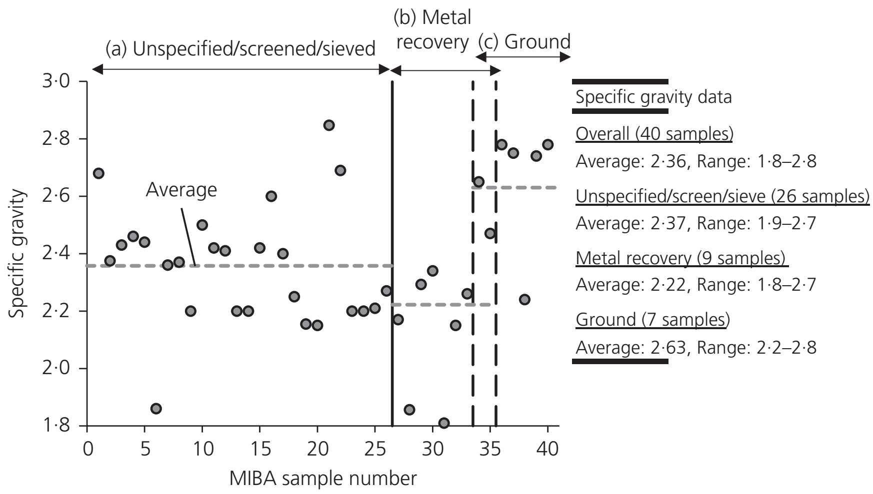

Figure 3. Density results of MIBA for (a) unspecified treatment/screened/sieved samples (b) samples subjected to metal recovery treatment and (c) samples ground to cement size fraction

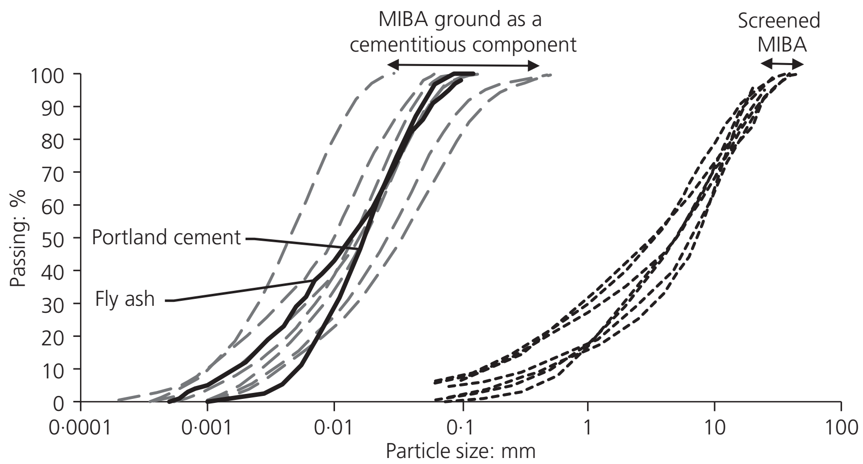

Figure 4. Particle size distribution curves of MIBA samples screened and ground as a cementitious component

components. Based on the total samples, the material had an average specific gravity of 2·36 (references in Appendix 5 of the Supplementary Material), however the process of recovering the denser metal fractions led to a decrease, and the process of grinding, which is a prerequisite for its use a cementitious component, led to an increase due to the smaller, more compact particles and lower porosity. In ground form (average specific gravity of 2·63), the density of the material is significantly lower than the typical value of 3·15 for Portland cement, although above the 2·3 value of fly ash (Jackson and Dhir, 1996).

Grading

After incineration, the residual MIBA contains a mix of metallics, ceramics, stones, glass fragments and unburnt organic matter and, despite the term 'ash', can contain large particles up to 100 mm in size. The material typically then goes through a screening process to remove the oversized fraction. For use as a cementitious component, the material is subsequently ground to powder size. Particle size distribution curves for screening MIBA and samples ground for use in concrete are presented in Figure 4 (references in Appendix 6 of the Supplementary Material) and show that the ground ash achieved well-graded distributions comparable to Portland cement and fly ash.

Grindability has not been a point of focus in the reported data on the characterisation of MIBA. Metals tend to have a high degree of hardness, and it is expected that these constituents in MIBA would be more difficult to grind. However, with common ferrous and non-ferrous metal recovery treatments of the ash after incineration, combined with the previously highlighted metallic aluminium expansion concerns that may necessitate further treatment, the quantity of the metal constituents may be notably reduced. It is interesting to note that, in a study on alternative energy sources in cement manufacturing, Albino *et al*. (2011) reported that the use of MSW would lead to savings in coal grinding energy costs.

Morphology

The ash contains irregular, angular shaped particles with a porous microstructure, arising from the heating and cooling process during combustion (references in Appendix 7 of the Supplementary Material). In this as-produced form, the higher specific surface area, porosity and associated water absorption properties suggest that the material would lead to an increase in the water demand of the concrete.

Use as a cement component in concrete-related applications

Raw feed in cement clinker production

The use of MIBA in cement clinker manufacture can reduce carbon dioxide emissions and contribute to the clinker compounds formation with its calcium, silicon, alumina and iron oxide contents. A description of the work undertaken with MIBA in this area is presented in Table 2, outlining its use as a minor component, at contents from 2–10% of the cement clinker feed.

To ensure the same main clinker phases are produced with MIBA, the silicon dioxide, calcium oxide, aluminium oxide and iron oxide contents and source materials were precisely regulated. As such, MIBA clinkers had chemical compositions comparable to the control (Table 2). However, at the upper end of the tested MIBA contents, the concurrent build-up of minor constituents such as phosphorus pentoxide and sulfur trioxide led to the suppression of tricalcium silicate (C_3S) formation, which consequently affected strength and setting behaviour, although it improved sulfate susceptibility. Chlorides in the ash can also lead to corrosion of kiln equipment in the long term and, as a result, the MIBA samples used by Pan *et al*. (2008) were washed prior to their inclusion in the cement clinker feed.

Based on the above data, it is expected that MIBA could be viably incorporated in cement clinker feed at low contents (up to about 5% has been suggested) without compromising performance. There may also be scope for higher MIBA contents to be incorporated if the phosphorus pentoxide, sulfur trioxide and chloride contents of the material are particularly low. Given the vast size of the cement manufacturing industry, with European Union countries reported to have produced 250 Mt in 2015 (Cembureau, 2015), it is projected that around 80% of the ash generated in these countries would be consumed through this use alone, if the 5% MIBA content was adopted throughout.

Of further interest, a number of additional studies utilised combined ash (MIBA and fly ash) as part of the raw feed for cement clinker production (Kikuchi, 2001; Shih *et al*., 2003; Torii *et al*., 2003; Wiles and Shepherd, 1999).

Cement component

This section examines the use of MIBA in ground form as a binder component in cement pastes.

Despite serious concerns regarding potentially damaging expansive reactions arising from the presence of metallic aluminium (covered in the section 'Material characteristics'), much of the work undertaken did not include additional treatment of MIBA beyond standard grinding (Fernandez *et al*., 1998; Filipponi *et al*., 2003; Giampaolo *et al*., 2002; Kim *et al*., 2016; Kokalj *et al*., 2005; Polettini *et al*., 2000;

Table 2. Description of works undertaken and emerging findings on the use of MIBA as part of the raw feed for cement clinker production

Work undertaken and findings
Krammart and Tangtermsirikul (2003, 2004)
Trials with cement clinkers containing 5% and 10% MIBA
MIBA clinkers had similar chemical compositions to the control. Lower compressive strengths were evident, although it had less susceptibility to sulfate expansion
Lam *et al*. (2010, 2011)
MIBA at contents of 2, 4, 6 and 8% in cement raw feed
Clinker containing up to 6% MIBA showed phase composition similar to Portland cement clinker, although 8% led to suppression of the main phases (decreased C_3S) due to phosphorus pentoxide and sulfur trioxide contents
Li *et al*. (2016)
Two clinkers – control and clinker with 9% MIBA + lower limestone, sandstone, fly ash and slag
Major chemical components of the MIBA and control clinkers were similar, though the MIBA blend had higher alkalis (sodium oxide and potassium oxide) and phosphorus pentoxide contents
Pan *et al*. (2008)
Cement clinker produced using 3·5% washed MIBA
Allowable MIBA was limited by its chloride content. Setting time increased with MIBA, while compressive strength was similar to the control clinker when phosphorus pentoxide was limited

Whittaker *et al*., 2009). Others researchers adopted chemical activation or thermal treatments for general improvement of the mechanical properties (Lin and Lin, 2006; Lin *et al*., 2008; Onori *et al*., 2011; Polettini *et al*., 2005, 2009), while Tang *et al*. (2014b, 2016) carried out a series of grinding plus thermal treatments on MIBA, specifically aiming to reduce the damaging expansive behaviour.

Compressive strength results are presented in Figure 5 for cement pastes using MIBA after standard processing (typically grinding) (Figure 5(a)) and chemical activation with calcium chloride ($CaCl_2$), calcium sulfate ($CaSO_4$) or high-temperature treatment (Figure 5(b)). The large strength losses evident with only a standard grinding treatment can likely be attributed, for the most part, to the detrimental expansion behaviour arising due to the reactive metallic aluminium in MIBA. As such, it is expected that additional treatment of the material would be essential for its use in this application. One exception in Figure 5(a) (Kokalj *et al*., 2005) did achieve good strength performance, although this was because the ash sample used in this work originated from a light fraction of MSW that contained minimal metals.

Specific testing of hydrogen gas development confirmed an increase in expansive gases with increasing MIBA content, reaching 4% of the volume of the tested cylinder at the highest tested MIBA content (30%) (Kim *et al*., 2016). Thermal treatment of MIBA to reduce the metallic aluminium was effective when combined with a subsequent lower speed grinding technique that allowed the ductile metallic aluminium to form into plate shapes to be subsequently removed during sieving, thus greatly reducing the metallic aluminium (Tang *et al*., 2016).

Additional chemical or thermal treatments have been found to be effective in improving the MIBA strength performance (Figure 5(b)), though they were not specifically focused on metallic aluminium reduction. Chemical activators alter the mineralogical composition to promote greater formation of hydration products, while thermal treatment converts the ash into a highly glassy material with enhanced reactivity. Some of the chemical activation processes involved a low heat treatment (90°C for 3 h) of the slurry of ground MIBA with activator. The best results were achieved with calcium chloride as the activator, exceeding the control strength at times, followed by calcium sulfate, while sodium metasilicate nonahydrate ($Na_2SiO_3.9H_2O$), sodium hydroxide (NaOH), sodium sulfate (Na_2SO_4), potassium hydroxide (KOH) and potassium sulfate (K_2SO_4) (results not shown) were not effective. Pastes using melted MIBA slag achieved compressive strengths close to the control at cement replacement levels up to 20%.

The large strength losses with the standard processed MIBA were symptomatic of poor overall performance, with corresponding reductions in density along with increases in porosity, absorption and additional cracking problems also evident in these pastes (Fernandez *et al*., 1998; Kim *et al*., 2016; Polettini *et al*., 2000; Tang *et al*., 2014b, 2016).

Heat flow analyses showed that MIBA, at contents up to 40%, led to a retardation of the hydration of the pastes and lower

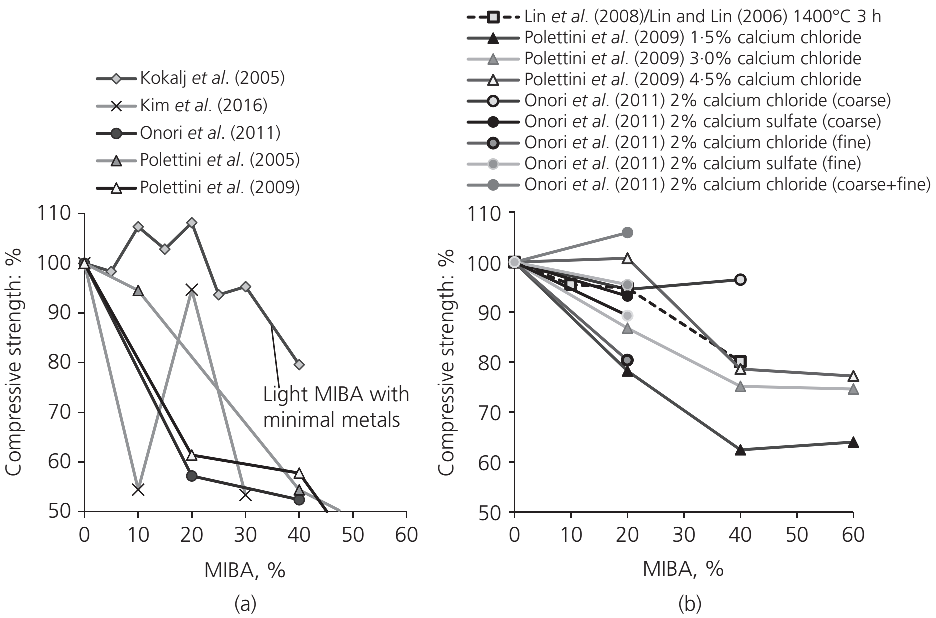

Figure 5. Effect on cement paste compressive strength with MIBA subjected to (a) standard processing and (b) additional chemical or thermal treatments

maximum heat releases (Onori *et al*., 2011; Tang *et al*., 2014b, 2016; Whittaker *et al*., 2009), attributed to the organic fraction and the presence of zinc and phosphate. Increases of 7–57% in initial and final setting times were also reported (Kim *et al*., 2016; Whittaker *et al*., 2009), including samples with melted MIBA slag (Lin and Lin, 2006; Lin *et al*., 2008).

As quantified from pozzolanic activity tests, MIBA did make a tangible contribution to the hydration reactions. Frattini and lime saturation tests, which directly measured the quantity of calcium hydroxide ($Ca(OH)_2$) in the presence of MIBA, revealed that the material generally satisfied the pozzolanic activity requirements and, when compared to established materials, performed similarly to fly ash and natural pozzolan (Fernandez *et al*., 1998; Filipponi *et al*., 2003; Giampaolo *et al*., 2002; Polettini *et al*., 2005, 2009). Melting treatment was found to be effective in increasing the amorphous phases in MIBA (Lin and Lin, 2006; Lin *et al*., 2008), while chemical activation was also found to further support the development of pozzolanic reactions in the pastes (Onori *et al*., 2011).

Mortar

As a cementitious component in mortar mixes, MIBA has been subjected to the prerequisite grinding processing, but additional thermal treatments have also been applied to the material. With the use of MIBA as cement replacement at contents up to 50%, the effects on the mortar fresh properties are presented in Table 3. The addition of MIBA generally led to minor decreases in the mix flow values, which can be attributed to the irregular particle shape and high porosity of the material. Additional thermal treatment did not significantly alter the effect of MIBA on mortar workability. Moderate increases in setting times were evident, which is expected when using pozzolanic materials as a replacement for Portland cement. The lower specific gravity of MIBA led to a slight reduction in fresh unit weight, whilst its higher water retention resulted in lower bleeding.

Regarding hardened properties, the effect of MIBA as a binder on the development of mortar compressive strength with age is shown in Figure 6(a) for ash samples subjected to the standard grinding treatment and in Figure 6(b) for samples with an additional thermal treatment. The results are presented as a percentage of the control at the same age and, as such, positively sloped lines imply that the pozzolanic activity of the material contributes to greater later age strength development.

This greater rate of later strength development was evident in most MIBA mixes. As is generally the case with pozzolanic materials, due to the delayed pozzolanic reaction, lower early age strengths were evident. However, thermal treatments (Figure 6(b)) were noted to improve the material reactivity, leading to both higher early strengths and long-term strengths that exceeded the control mix. Additional work by Carsana *et al*. (2016) and Tang *et al*. (2016), with treatments specifically aimed at reducing the metallic aluminium, showed that the associated expansive reaction can have a drastic impact on strength performance. Reductions in metallic aluminium contents and much improved mechanical performance were

Table 3. Fresh properties of mortars using MIBA as a cementitious component

Reference	Mortar fresh properties
Consistency	
Cheng *et al*. (2011)	MIBA ground to <74 μm. Minor decreases in flow from 131 mm (0% MIBA) to 109–123 mm with 10–40% MIBA. All mixes deemed to have satisfactory workability
Saccani *et al*. (2005)	MIBA thermally treated (1500°C, 4 h), quenched and ground. Increased flow table values of 75 mm (20% MIBA) and 70 mm (30% MIBA) compared with the control 60 mm (0% MIBA)
Tang *et al*. (2014a, 2016)	MIBA ground or MIBA ground + thermal treatment (550/700°C). Thermal treatment did not have a significant effect on flow. All flows with 20% MIBA were within +5 mm to −10 mm of the control
Whittaker *et al*. (2009)	MIBA ground to 2 μm. More sizeable reductions in flow table results from the control (190 mm), to 167 mm for 10% MIBA and 136 mm for 40% MIBA
Zhang and Zhao (2014)	MIBA ground to 40 μm. Slight increases in water demand with increasing MIBA content, rising from 26·1% for 0% MIBA to 30·1% for 50% MIBA
Setting time	
Cheng (2012)	MIBA ground to < 74 μm or melted (1450°C) and ground. Initial and final setting times were increased (up to 30% longer with 40% MIBA). Melting did not significantly alter the rate of delay
Saccani *et al*. (2005)	MIBA vitrified (1500°C, 4 h) and quenched and ground. With 30% MIBA, initial setting time increased from 60 to 100 min and final setting time increased from 170 to 235 min
Zhang and Zhao (2014)	MIBA ground to < 40 μm. Increases in initial and final setting times of approximately 40% for the highest tested 50% MIBA content
Fresh unit weight	
Cheng (2012)	MIBA ground to < 74 μm. Minor decrease in fresh unit weight with up to 40% MIBA, also accompanied by minor increases in the mix air contents
Bleeding	
Cheng (2012)	MIBA ground to < 74 μm. Decrease in bleeding from 0·1988 ml/cm^2 for control (0% MIBA) to 0·1395 ml/cm^2 for 40% MIBA

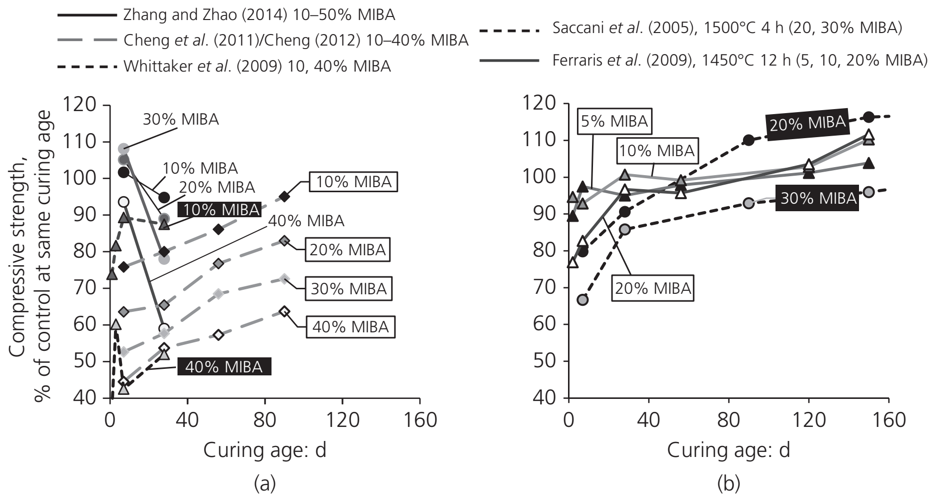

Figure 6. Compressive strength development of mortars using MIBA subjected to (a) standard processing and (b) additional thermal treatment

achieved using a combined metal separation plus wet grinding treatment (Carsana *et al*., 2016) and a combined thermal plus lower speed grinding treatment (Tang *et al*., 2016).

The wet grinding step is particularly effective because the aluminium fractions become more exposed as the particles fragment during grinding (Carsana *et al*., 2016) and, in the alkaline environment, the expansive reactions develop from the formation of aluminium hydroxide and hydrogen gas and are eventually depleted before the material is introduced into the cement mixture. A slower grinding speed can also be beneficial as it allows better removal of the dust-like particulates that reside on MIBA particle surfaces (which are believed to be the most reactive fractions) by means of inter-particle friction and, as a result, the subsequent expansive reactions in the cement environment are reduced (Tang *et al*., 2016).

In addition to hydrogen gas expansion, the effects of MIBA on a number of other aspects of mortar durability have been examined.

- *Drying shrinkage*. Using ground MIBA, the drying shrinkage of mortar mixes increased with increasing MIBA content, accompanied by increases in porosity. However, after thermal treatment (maximum temperature of 1450°C for 12 h), the opposite behaviour was evident: the MIBA mixes had less drying shrinkage than the control, due to the lower porosity and denser microstructure associated with the greater pozzolanic reactions and filling effects (Cheng, 2012; Cheng *et al*., 2011).
- *Ingress of chlorides and sulfates*. The use of thermally treated (1500°C for 4 h) MIBA as a cement replacement in mortar reduced the depth of penetration of chlorides and sulfates (Saccani *et al*., 2005). Again, this can be linked to the lower porosity of the MIBA mixes.
- *Alkali–aggregate reaction*. Accelerated tests on alkali–silica reactivity showed that thermally treated MIBA as a replacement of 20% or 30% of the cement led to a significant reduction in the mortar expansion (Saccani *et al*., 2005), as is typically expected with the use of pozzolanic materials due to a dilution in alkalinity.

Concrete

The use of MIBA as a cement component in concrete mixes is expected to show similar behaviour to its use in mortar, with the potential hydrogen gas expansion likely to dictate that additional treatment of the ash, after grinding, should be undertaken. Concrete compressive strength results are presented in Figure 7, in the same manner as the mortar results in Figure 6, using MIBA (as binder) subjected to standard processing (Figure 7(a)) and an additional thermal treatment (Figure 7(b)).

The concrete results appear to be more positive than the mortar counterparts, achieving later age strengths comparable to the control in some cases (Bertolini *et al*., 2004, 2005 (wet-ground); Jaturapitakkul and Cheerarot, 2003; Jurič *et al*., 2006). Hydrogen gas expansive reactions were surprisingly only reported by Bertolini *et al*. (2004), with dry-ground MIBA. The wet grinding process (slurry with a 1:1 solid/liquid ratio) led to the dissipation of the expansive reactions (i.e. the formation of visible gas bubbles). With a subsequent rest period before use of the MIBA (2 d was sufficient in the studies of Bertolini *et al*. (2004, 2005) though this may vary), the metallic aluminium reactions can be depleted, thus leading to drastic strength and density improvements. The additional thermal treatment, although a more energy-intensive option (1450°C for 1 h; Cheng *et al*., 2011), produced a more reactive MIBA slag due to its higher amorphous fraction, which also led to improvements in the compressive strength (Figure 7(b)).

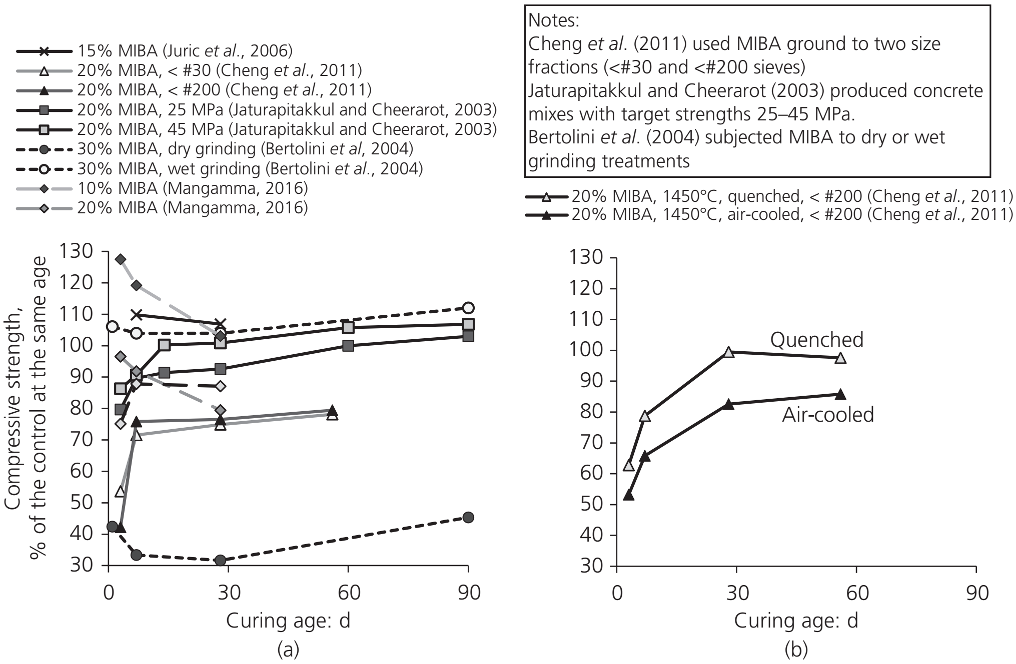

Figure 7. Compressive strength development of concrete using MIBA subjected to (a) standard processing and (b) additional thermal treatment

Mixed findings are reported regarding the effect of MIBA on the concrete mix consistence. With 30% of the cement replaced, the slump decreased from 60 mm to 0 mm with the finer wet-ground MIBA ($d_{50} = 3$ μm), compared to an increase to 110 mm with the dry-ground MIBA ($d_{50} = 15$ μm) (Bertolini *et al.*, 2004, 2005). Additional slump increases from 162 mm (control) to 167–187 mm for ground and thermally treated MIBA (passing 74 μm) were reported by Cheng *et al.* (2011), although a contrasting drop from 105 mm (control) to 44 mm with 15% MIBA (unspecified fineness) was reported by Jurič *et al.* (2006). Differences in the ash fineness after grinding contributed somewhat to variability in the workability, with increased fineness found to lead to lower slumps. The moisture content of MIBA prior to its use is another important variable to consider. The irregular shape of the ash particles and the porous microstructure of the material also point towards an expected reduction in the mix consistency with MIBA, for a given water content.

Regarding concrete permeation properties, the inclusion of 20% ground MIBA reduced the initial surface absorption test value from 0·6 to 0·3 ml/m^{2}s. Additional thermal treatment was also beneficial in achieving a denser concrete microstructure due to the increased pozzolanic activity (Cheng *et al.*, 2011).

As a measure of the concrete corrosion resistance, open circuit potential results matched up consistently with the compressive strength performance (see Figure 7), with ground plus melted MIBA mixes performing similarly to the control and mixes with only ground MIBA showing greater susceptibility (Cheng *et al.*, 2011). This same behaviour with MIBA mixes was also evident in rapid chloride penetration tests to measure the electric current passing through (Cheng *et al.*, 2011). Results on indirect electrical resistivity and direct chloride apparent diffusion coefficients revealed that the higher strength wet-ground MIBA mixes had greater resistance than the control, while the lower strength dry-ground MIBA mixes were less resistant (Bertolini *et al.*, 2004, 2005). Overall, the initial testing suggests that, for equivalent compressive strength, mixes with MIBA as a binder will deliver resistance to chloride ingress on a par with or greater than a control Portland cement mix.

Controlled low-strength materials (CLSMs)

Controlled low-strength materials are used as an alternative to soils as backfill material, with their main characteristics (including high flowability, self-compacting, self-curing properties and strengths) controlled to low levels to allow future excavation. As outlined in the American Concrete Institute guidance report on CLSM (ACI, 2005), these products typically contain fly ash as filler, low contents of cement, coarse and fine aggregates and water.

Initial work undertaken with MIBA adopted a more unconventional approach, using a mix of dewatered sludge (DS) + calcium sulfoaluminate cement (CSA) + water as the control, with MIBA (ground to less than 4 mm) replacing up to 80%

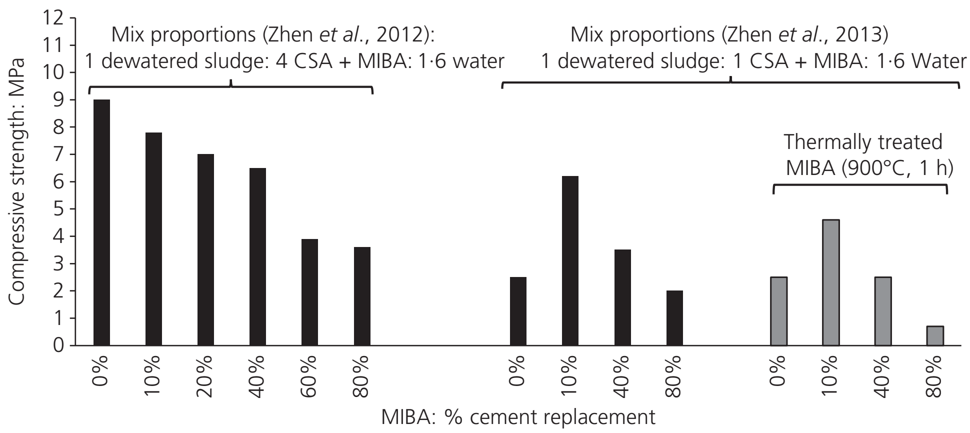

Figure 8. Compressive strength of CLSMs after 28 d using MIBA as a cement (CSA) replacement

of the cement (Zhen *et al*., 2012, 2013). The focus of the testing was on compressive strength development, and the results are presented in Figure 8. CLSMs with mix proportions of one or four units of CSA (or CSA + MIBA) per unit of DS were produced. A few of the MIBA samples used were subjected to an additional thermal treatment at 900°C for 1 h. Other important properties, such as flowability and compactability, have not been covered thus far.

These CLSMs produced using MIBA appear to be more suited towards structural applications, as all the mixes greatly exceeded the 0·3 MPa (50 psi) manual excavation guidance limit and all but two (CLSMs with 80% MIBA and the lower total CSA + MIBA proportion) exceeded the machine excavation limit of 2·1 MPa (ACI, 2005). Accompanying analyses of the microstructure and mineralogy (x-ray diffraction, thermogravimetry/differential scanning calorimetry and scanning electron microscopy/energy dispersive x-ray spectroscopy) by Zhen *et al*. (2012, 2013) suggested that the MIBA did contribute to the strength performance, despite the consistent strength decreases with increasing MIBA contents in the 1 DS: 4 CSA + MIBA: 1·6 water mixes. However, the use of MIBA or other pozzolanic material with CSA may not be an effective combination, as this cement type is less alkaline and does not produce the calcium hydroxide needed for pozzolanic reactions (Pera and Ambroise, 2006). The increase in strength with low MIBA contents in the lower CSA + MIBA mixes may be partly due to improved mechanical filling. Thermal treatment of MIBA for use in CLSMs did not have a favourable effect on the mechanical performance.

Aerated concrete

Aerated concrete appears to be an ideal application for MIBA as the hydrogen gas expansive reactions arising from metallic aluminium in the material can make a positive contribution towards the desired low-density properties. In the works undertaken thus far, MIBA has served as a valuable aerating agent whilst also making a useful contribution to the silica required for strength development.

Prior to the implementation of MIBA in aerated mixes, the response of the material to varying levels of alkaline solution (0·0016–1 mol/l of sodium hydroxide or calcium hydroxide) was examined by measuring hydrogen gas production at temperatures from 40 to 70°C (Chen *et al*., 2014; Song *et al*., 2015, 2016; Wang *et al*., 2016, Yang *et al*., 2015). The results were converted to a standard measure of volume of hydrogen gas per gram of powder at 1 atm (pressure) and 23°C. The following findings have been reported.

- The volume of hydrogen gas produced increased with MIBA fineness. This can be attributed to the increased specific surface area and greater exposure of the reactive components associated with higher particle fineness. The finest MIBA fraction (average particle size of 23·2 μm) produced approximately 1% of the gas produced by aluminium powder per gram in equivalent conditions.
- Hydrogen gas production increased both as the temperature rose and conditions became more alkaline (higher alkaline solution molarity). Comparable results were achieved with either sodium hydroxide or calcium hydroxide as the alkaline solution.

The mix designs for aerated concrete containing MIBA are presented in Table 4, along with the density and compressive strength results. Differing approaches have been adopted, using MIBA as a replacement for cement, coal fly ash or circulating fluidised bed combustion (CFBC) fly ash, along with variations in the other constituents, alkaline solutions and molarity, and water content.

As a cement replacement, increasing MIBA and sodium hydroxide molarity led to increasing porosity and associated reductions in density and compressive strength (Chen *et al*.,

Table 4. Mix designs and density and compressive strength results for aerated concrete

Mix design						Density: kg/m^3	Compressive strength: MPa
Cement replaced (Chen *et al*., 2014; Song *et al*., 2016; Yang *et al*., 2015) Other variables: alkaline solution type and molarity, *L/S* ratio							
Cement	MIBA	Sand	Alkali solution		Liquid/solid (L/S) ratio		
4	1	5	Water		0·175	1554	19·5
4	1	5	0·01 mol/l sodium hydroxide		0·175	1512	16·0
4	1	5	0·1 mol/l sodium hydroxide		0·175	1444	12·5
4	1	5	1 mol/l sodium hydroxide		0·175	1324	5·7
3	2	5	1 mol/l sodium hydroxide		0·35	1056	2·7
2	3	5	1 mol/l sodium hydroxide		0·35	932	1·5
Coal fly ash replaced (Song *et al*., 2015; Yang *et al*., 2015) Other variables: comparison to aluminium powder							
Cement	MIBA	Coal fly ash	Aluminium powder	Lime/ gypsum	Water		
10	0	67	0	20/3	65	1074	13·9
10	5	62	0	20/3	65	846 (↓ 21%)	9·7 (↓ 30%)
10	10	57	0	20/3	65	728 (↓ 32%)	8·4 (↓ 40%)
10	20	47	0	20/3	65	673 (↓ 37%)	7·2 (↓ 49%)
10	30	37	0	20/3	65	637 (↓ 41%)	6·1 (↓ 56%)
10	0	67	0·05	20/3	65	831 (↓ 23%)	7·7 (↓ 45%)
10	0	67	0·1	20/3	65	673 (↓ 37%)	6·5 (↓ 53%)
10	0	67	0·2	20/3	65	603 (↓ 44%)	4·1 (↓ 71%)
10	0	67	0·3	20/3	65	511 (↓ 52%)	2·9 (↓ 79%)
CFBC fly ash replaced (Wang *et al*., 2016) Other variables: none							
Cement	MIBA	CFBC fly ash		Lime	Water		
10	0	70		20	65	1116	18·1
10	5	65		20	65	868 (↓ 22%)	17·1 (↓ 5%)
10	10	60		20	65	799 (↓ 28%)	13·2 (↓ 27%)
10	20	50		20	65	656 (↓ 41%)	8·9 (↓ 51%)
10	30	40		20	65	613 (↓ 45%)	6·8 (↓ 63%)

2014; Song *et al*., 2016; Yang *et al*., 2015): the density was affected more by the MIBA content, whilst the alkaline solution molarity had a greater influence on strength. The substitution of MIBA for coal and CFBC fly ashes also resulted in reductions in density and strength due to the increased expansive reactions and porosity (Song *et al*., 2015; Yang *et al*., 2015). The strength-to-density ratio for the mixes containing MIBA was lower than that of the coal and CFBC fly ashes, but was higher than the ratio when using aluminium powder (1 g of MIBA for 0·01 g of aluminium powder based on the previous hydrogen gas experiments). As such, the use of MIBA and these fly ashes appears to be an ideal combination that can produce the desired low density, with better strength than the aluminium powder mixes and, at the same time, saves the cost of expensive aluminium aerating agents.

The drying shrinkage of MIBA aerated concrete was found to stabilise at around 15 and 20 d respectively for the CFBC fly ash and coal fly ash mixes. Consistent increases in shrinkage were evident with increasing MIBA content, due to the higher porosity and associated increased ease of moisture loss and the lower resistance to movement due to the lower strength. Despite this increased susceptibility, the drying shrinkage values of all the MIBA aerated concrete mixes were within the targeted Chinese national standard limit of 0·50 mm/m (Song *et al*., 2015; Wang *et al*., 2016).

Conclusions

The chemical composition of municipal incinerated bottom ash (MIBA), with main oxides of silicon dioxide, calcium oxide and aluminium oxide, combined with its amorphous fraction, indicates that it may have pozzolanic properties in ground form. The ash contains notable contents of sulfur trioxide, chlorides and organic matter. These should be monitored, and treatment may be required at times to limit the negative impacts on concrete performance. Metallic aluminium in MIBA is also a key concern that may demand treatment to avoid damaging expansive reactions. In ground form, MIBA was found to have an average specific gravity of 2·6, placing it above fly ash and below Portland cement. Its irregularly shaped particles, porous microstructure and higher absorption properties indicate that MIBA may lead to a rise in the concrete water demand.

As raw feed in cement clinker production, MIBA can be viably used at low contents (recommended up to 5%) to produce cement clinker comparable to the control. At higher MIBA contents, the build-up of phosphorus pentoxide and sulfur trioxide affects the setting and strength development. Washing treatment may also be implemented to reduce long-term corrosion of kiln equipment due to the chlorides in MIBA.

As a cementitious component in paste, mortar and concrete mixes, treatment of MIBA beyond standard grinding is needed to avoid expansive reactions and the associated negative effects on strength, density, absorption and cracking arising from the metallic aluminium in the ash. Thermal and chemical activation treatments have been shown to be effective in improving strength performance, while tailored slow and wet grinding techniques targeting the removal of metallic aluminium have also resulted in drastic increases in performance. MIBA contributed to strength development as a partial cement replacement, achieving long-term strengths greater than the control mortar and concrete mixes, after suitable treatment. Increases in the water demand and setting times were evident when MIBA was used as a binder in mortar and concrete. With regards to permeability, drying shrinkage, chloride and sulfate ingress and alkali–aggregate reaction, products containing appropriately treated ash performed comparably to or better than control mixes at equivalent strengths.

MIBA appears suited for use in aerated concrete, as the hydrogen gas expansive reactions can contribute towards the desired low-density properties, serving as an alternative to costly aerating agents such as aluminium powder and also as a source of silica for strength development. MIBA has been incorporated in varying mix designs as a replacement for cement, coal fly ash or circulating fluidised bed combustion (CFBC) fly ash, with large reductions in density achieved. The use of MIBA in combination with coal fly ash also achieved a superior strength-to-density ratio as compared with mixes with aluminium powder, in addition to saving the cost of the aerating agent. Initial work on controlled low-strength materials has also indicated MIBA as a potential cement replacement that can meet the low-strength requirements of this application.

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